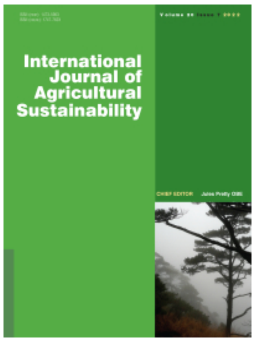

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Assessment of agricultural sustainability performance in Dali Prefecture, China using the DPSIR Model

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ABSTRACT

Urbanization and ecological efforts in China have significantly altered agricultural land use affecting both the quantity and quality of arable land. There has been a rise in the use of energy, fertilizers, pesticides, and plastic films to enhance production. However, these unsustainable farming practices have led to higher greenhouse gas emissions and the risk of agricultural non-point source pollution. The Yunnan Province government aims for sustainable agriculture to enhance product quality and China's green farming. Yunnan's proximity to the Yangtze, Lancang, and Yuan Rivers makes agriculture vital for the downstream livelihoods and biodiversity. This study explored factors affecting agriculture in Dali Prefecture, Yunnan Province. The study proposed a comprehensive system of 33 indexes to assess agricultural sustainability performance using the Driver-Pressure-State-Impact-Response framework. It employed a composite weight method combining the Analytic Hierarchy Process and Entropy Weight methods. The assessment showed that all counties except Dali City scored a performance index below 0.5. Furthermore, the "Response" indicator was found to be crucial in advancing agricultural sustainability. Conversely, factors leading to unsustainable changes, like "Driver" were less significant. The study reveals that data statistics prioritize indexes related to land resources while experts emphasize indexes linked to socioeconomic status when assessing agricultural sustainability.

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KEYWORDS
Agricultural sustainability; urbanization; land use change; rural decline; DPSIR; ecological protection; Southwest China

1. Introduction

Before 1978, China was mainly an agricultural country, with over 80% of the population residing in rural areas and depending on farming for survival (Chen et al., 2014). Significant changes occurred with the implementation of economic reforms and the open-door policy in 1978 (Zhou et al., 2020), leading to a profound socio-economic transformation in China that affected all sectors (Liu, 2018). The urbanization rate in China experienced a significant increase from 18% in 1978 to 56.1% in 2015 and further rose to 64.72% in 2021 (NBSC, 2023). This rapid urbanization resulted in the expansion of urban areas and a considerable reduction of arable land (Huang et al., 2015; Tu et al., 2018). Between 1978 and 1985, China's total arable land area decreased from 99.5 million hectares to 96.2 million hectares, with an average annual decrease of 0.47 million hectares (Zhou et al., 2020). The demand for urban construction surged, encouraging hundreds of millions of rural labourers to migrate to urban areas (Chang & Brada, 2006). The number of rural labourers moving to urban areas increased from 72 million in 1996 to 288 million in 2018 (Zhou et al., 2020).

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As arable land diminishes, a growing population and increased food demand have driven agricultural expansion onto grasslands, forests, and hillsides. Soil erosion poses a pressing environmental challenge in China, contributing 2–4 billion tons of silt into the Yangtze and Yellow Rivers annually, with 65% originating from cultivated slopes (Xie et al., 2022). To combat soil erosion, the Chinese government initiated a state-led Payments for Ecosystem Services called the Sloping Land Conversion Program (SLCP) in 2000 (He & Sikor, 2015; Xie et al., 2022). This initiative successfully converted 4.34% and 3.09% of cultivated land into forestry and grassland, respectively, between 2009 and 2019 (Chen et al., 2022). Additionally, the Returning Farmland to Forest and Grassland Projects, in effect since 1999, had replaced 13.73 million hectares of farmland with forest and grassland by 2019 (NFGA, 2020). These ecological restoration effects have significantly reduced the total cropland area and the amount of cropland per rural household in China (Ge et al., 2018; Wang et al., 2014). The per capita cropland area in China decreased from 0.19 hectares in 1952 to 0.09 hectares in 2008 (Wang et al., 2012).

In 1998, the 'Basic Farmland Protection Regulations' was enacted to safeguard national food security by prohibiting the use of basic farmland for non-agricultural purposes (Liu et al., 2014). The Requisition-Compensation Balance of Farmland (RCBF) policy, implemented in 1997, required each county-level unit to reclaim an equivalent amount of new land for agriculture to offset losses caused by non-agricultural activities (Lin et al., 2018). However, the occupied arable land is typically of high quality, while newly reclaimed land often comes from low-quality unused land (Chen et al., 2022; Wang et al., 2012), leading to invisible degradation in arable land quality and a corresponding decline in agricultural productivity (Chen et al., 2022). For instance, in 2005, roughly 67% of arable land converted into developed areas had irrigation facilities, while only 35% of newly reclaimed arable land had such facilities (Wang et al., 2012). Despite a decrease in the proportion of arable land used for non-agricultural purposes due to farmland protection policies (Wang et al., 2012), the total amount of arable land declined from 127.6 million hectares in 2001 to 121.73 million hectares in 2007. To boost land productivity per capita, farmers often increase agrochemical and energy inputs (Wang et al., 2014; You et al., 2018). However, these practices contribute to rising greenhouse gas emissions and potential agricultural non-point source pollution, further affecting the quality of local land, groundwater, surface water, and agricultural products (Wang et al., 2014).

In September 2015, 193 countries signed the new United Nations development agenda, emphasizing 17 Sustainable Development Goals (SDGs) and 169 targets. These goals aim to promote the sustainability of human society and the global environment (Hu et al., 2022; Kanter et al., 2016). Agriculture plays a crucial role in achieving these SDGs due to its close ties to various sustainable development challenges (Bastan et al., 2018; Kanter et al., 2016, 2018). Among that, the key challenge confronting the agricultural sector is to feed the steadily increasing global population, with food demand expected to grow by 60% by 2050 while also mitigating agriculture's environmental footprint and safeguarding natural resources for future generations (Arhin et al., 2024; Meng et al., 2024). The sustainable development of agriculture should be an ongoing paradigm (Bastan et al., 2018). In today's era of sustainable development, transforming the agricultural sector toward sustainability requires optimizing agronomic, environmental, and socioeconomic outcomes while monitoring their interactions and assessing progress toward SDGs (Kanter et al., 2018). Therefore, evaluating agricultural sustainability involves a thorough analysis of all factors influencing different sectors related to agriculture and understanding the complex interplay between these influences (Bastan et al., 2018; Kanter et al., 2018).

Yunnan's agricultural products are sold across over 150 major cities domestically and exported to more than 40 countries and regions worldwide. According to '14th Five-Year Plan for Building a World-Class 'Green Food Brand" issued by the Yunnan Provincial Government in November 2021, the provincial government aims to position Yunnan as a pioneer in China's green agriculture initiatives, a significant production region for green food, and a frontrunner of modern agriculture with local characteristics by 2025. As Yunnan transitions from 'quantity' to 'quality' in agricultural production and exports, there is a need for an assessment framework for agricultural sustainability. Meanwhile, Yunnan is in the upper reaches of the Yangtze River (which flows from east to west across China) and the Lancang River (Mekong River), extending into five Southeast Asian countries. It is also the source of the Yuan River (Red River), which flows into Vietnam. The sustainability of agriculture in Yunnan is essential for maintaining the health of the environment, human populations, and biodiversity downstream along these three rivers. To realize this vision, stakeholders must comprehend the multifaceted factors influencing agriculture, as agricultural sustainability is complex. Therefore, the development of a roadmap is essential to guide the assessment and improvement of agricultural sustainability. While existing case studies in China have focused on the East China (Geng et al., 2021; Lin & Hou, 2023) and North China (Hu et al., 2022), these areas not only exhibit economic development but also possess relatively flat terrain, which differs significantly from the socio-economic and topographical conditions found in the southwestern China. With less than six years remaining to achieve the Sustainable Development Goals outlined in the United Nations' 2030 Agenda, urgent action is needed to enhance agricultural sustainability. This study fills a gap by conducting the first assessment of agriculture sustainability in southwest China, an area characterized by less economic development and abundant mountainous terrain. While an Agro-Ecological Sustainability Index framework exists for assessing sustainability interventions in Yunnan, it overlooks societal systems. Agricultural sustainability is complex, involving environmental, social, economic, and resource use issues that vary across location, time, society, and priorities (Mishra et al., 2018). Various studies have proposed assessment systems and frameworks to assess agricultural sustainability. Hu et al. (2022) introduced an assessment system comprising three dimensions to assess sustainable agricultural and rural development in the Beijing-Tianjin-Hebei region at the county level. Expanding on the cause-and-effect relationship of the Driver-Pressure-State-Impact-Response (DPSIR) framework, Geng et al. (2021) established a 24-indicator framework for assessing agricultural sustainability across economic, social, and ecological dimensions. Khan et al. (2021) incorporated input and output into an index framework to assess rural sustainable development efficiency using a DPSIR analysis framework and super efficiency Slack-Based Measure (DPSIR-SBM) model. Diaz-Sarachaga (2020) proposed a rural revitalization plan aligned with the Sustainable Development Goals (SDGs) and Rural Development Program (RDP) priorities, focusing on economic, environmental, institutional and social four dimensions.

Given the significant impact of human behaviour on the ecosystem, it is crucial to have a comprehensive understanding of agricultural sustainability, which is the primary focus of this study. This paper has developed an assessment system for the agriculture sector using the DPSIR model, providing stakeholders with a roadmap for enhancing agricultural sustainability in Southwest China. The DPSIR model is valued for its ability to capture and simplify the relationship between social and environmental factors, making it useful as a communication tool between researchers from various disciplines, as well as between researchers, policymakers, and stakeholders (Svarstad et al., 2008). In the causal chain model, the long-term Drivers (D) initiate potential changes within the environment due to economic, social, and population factors. These Drivers create Pressure (P) on the environment, altering the State (S) of the social-ecological environment, which subsequently influences human society and the natural environment. This, in turn, triggers human Response (R) actions in response to changes and negative Impacts (I) caused by Drivers (Yu et al., 2020).

Using Dali Bai Autonomous Prefecture as a case, we applied this assessment system to assess the performance of agricultural sustainability at the county level and provide valuable insights. The study addresses three main questions: (a) What are the key indicators and indexes for assessing agricultural sustainability in Southwest China, and what is their ranking in terms of contribution? (b) What is the agricultural sustainability performance of each county within Dali Prefecture? (c) What measures can Dali Prefecture adopt to enhance its agricultural sustainability?

2. Materials and methods

2.1. Study area

Southwest China is one of seven natural geographical divisions in China (Figure 1). Although it covers 24.38% (around 234 million hectares) of China's total land area, the population in this region accounts for only 14.53% (about 205.15 million) of the country's total population. Characterized by intricate topography and diverse ecological settings (Gao et al., 2021), Southwest China includes the southeastern Qinghai-Tibet Plateau, the Sichuan Basin, and the majority of Yunnan-Guizhou Plateau. Serving as China's ecological security barrier due to its essential ecosystem services, Southwest China faces the dual challenge of balancing ecological preservation and economic development, resulting in socio-economic conditions that lag behind those of Eastern China (Sun et al., 2021). As a high-incidence region for drought, Southwest China often experiences

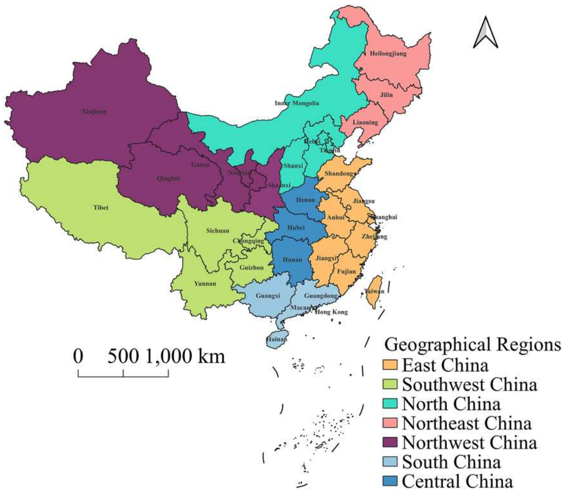

Figure 1. Natural geographical divisions of China.

droughts more frequently than south of the Yangtze River and South China at the same latitude (Ding & Gao, 2020).

Yunnan province stands out as one of the most plant-diverse terrestrial regions on Earth, situated within the Himalayan biodiversity hotspot (Zhang et al., 2012). Located near the southeastern border of the Qinghai-Tibet Plateau, Yunnan is a mountainous province in southwest China (Wang et al., 2021). Situated in a subtropical plateau monsoon zone with significant climate variations, Yunnan experiences distinct rainy seasons from May to October and dry seasons from November to April (Song et al., 2021; Yu et al., 2021). Annual average precipitation ranges between 600 and 2200 mm in Yunnan with spatial variability, while dry season precipitation accounts for only 15% of the total annual precipitation (Yu et al., 2021). Yunnan's environment shifts with elevation from north to south, while its climate varies with latitude (Yu et al., 2021), delineating three primary climatic zones based on elevations: subalpine (approximately 3000 m), subtropical (around 2000m) and tropical (approximately 600–800 m) (Song et al., 2021). Yunnan experiences dry and warm winds on the lee side of mountain ranges, known as the Foehn Effect (Yu et al., 2021), due to its predominantly mountains (88.64%) and hills (4.96%). The most suitable land for cultivation is in intermountain basins, known locally as 'Bazi', constituting about 6% of Yunnan's total area. Bazi includes various flat intermountain landforms such as tectonic basins, river terraces, alluvial fans, and foothills (Wang et al., 2021). Unfortunately, much of the high-quality arable land in the Bazi area has been claimed by urban construction activities. The increasing population and escalating food demand have led to expanded cultivation on steep slopes in Yunnan (Barton et al., 2004). From 1960 to 1990, forest coverage in Yunnan declined from approximately 60% to 24% (Barton et al., 2004). From 1986 to 2015, 33.55% of the land area of Yunnan Province experienced soil erosion (Rao et al., 2023). Meanwhile, inadequate soil conservation measures and inappropriate agricultural management strategies during farming have accelerated soil erosion (Barton et al., 2004). 88.2% of farmland in Yunnan has a slope steeper than 6°, and 18.2% has a slope steeper than 25°, presenting a substantial threat to Yunnan's food security due to the potential for severe soil erosion and land degradation (Xingwu et al., 2015). Maize is the dominated crop due to the majority of farmland in Yunnan features slopes exceeding three-degrees. At the same time, other agricultural products like rice, wheat, sugarcane, tobacco, and fruits are also cultivated (Fan et al., 2021). Red earths, constituting 30.97% of the total soil surface area, are the most prevalent soil type in Yunnan province, along with yellow-brown earths, which are dominant in West Yunnan (including Dali Prefecture, Dehong Prefecture, and Baoshan City) (Xingwu et al., 2015). Despite the presence of the Yangtze, Pearl, and Mekong rivers flowing through Yunnan province, it remains vulnerable to droughts due to uneven water distribution and insufficient water conservation infrastructure (Fan et al., 2021). Data reveals that 43% of meteorological disasters in Yunnan are droughts. In 2019, the drought from April to June affected 1.35 million hectares of crops, including 79,000 hectares crop failure, resulting in a direct economic loss of 6.562 billion yuan (Ding & Gao, 2020). Since 2000, with decreasing precipitation, drought events have increased in Yunnan, leading to an expansion in drought-affected areas and a shortened occurrence cycle from 2–3 years to 1–2 years (Ding & Gao, 2020).

The Dali Bai Autonomous Prefecture, commonly referred to as Dali Prefecture, is one of Yunnan's 16 prefecture-level administrative regions located in the northwestern part of Yunnan Province (Figure 2). It governs Dali City and 11 counties, situated between 98°52′~101°03′E, 24°41′~26°42′N. Positioned in an ecologically fragile transition zone from the lower Yunnan Plateau to the elevated Qinghai-Tibet Plateau, Dali Prefecture covers a total area of

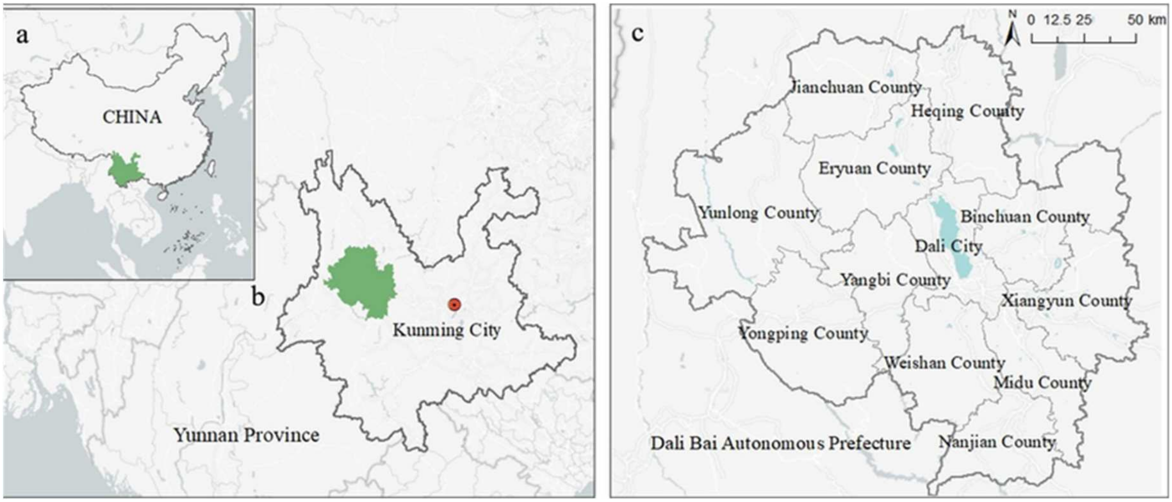

Figure 2. Study area. (a) China; (b). Yunnan Province; (c) Dali Bai Autonomous Prefecture. Source: Yin et al. (2023).

2,945,900 hectares, with over 93% being mountainous areas (Peng et al., 2019b). Situated at the junction of the Yunnan-Guizhou Plateau and the Hengduan Mountain Range, it features high terrain in the northwest and lower terrain in the southeast. Water resources, totalling 13.44 billion m^3, are primarily concentrated in the northwest region (Peng et al., 2019a). The annual average rainfall is between 800 and 1000 mm, and the average annual temperature is 15°C. Due to its challenging terrain (93.4% of the area being mountainous), Dali Prefecture has developed unique mountain agriculture. According to Peng et al. (2019b), the cropland in Dali Prefecture decreased from 375,260 hectares in 2009 to 370,628 hectares in 2016. In 2021, the grain planting area in Dali Prefecture reached 29.851 hectares, with a total grain output of 1.67 million tons.

2.2. Model description and data preparation

2.2.1 DPSIR model

In the 2000s, the Driver-Pressure-State-Impact-Response (DPSIR) framework gained broad acceptance by the EEA, OECD and UNEP for interdisciplinary indicator development, system and model conceptualization, and structuring integrated research programmes and assessments (Svarstad et al., 2008). The DPSIR model is valued for its ability to capture and simplify the relationship between social and environmental factors, making it a useful communication tool among researchers from various disciplines, as well as between researchers, policymakers, and stakeholders (Svarstad et al., 2008). This paper utilizes the DPSIR framework to suggest a comprehensive system with 33 indexes for assessing the performance of agricultural sustainable development (Table 1). Today, DPSIR is increasingly used in constructing case studies related to human activities, including its application for agricultural sustainability assessment (Geng et al., 2021), rural sustainable development efficiency (Khan et al., 2021), marine ecosystem service (Kelble et al., 2013), sustainable management of land and ecosystem services (Pullanikkatil et al., 2016), marine management (Atkins et al., 2011), reef fishing activities (Mangi et al., 2007), and the impact of upstream activities on the Mondego River estuary area (Pinto et al., 2013).

Figure 3 illustrates the causal relationship between DPSIR sectors, depicting the chain linkages from drivers to response and back to drivers (Geng et al., 2021). Drivers (D) describes large-scale socioeconomic conditions and sectoral trends (Mangi et al., 2007), such as rural decline and agricultural abandonment caused by urbanization, reflecting human needs and desires (Kelble et al., 2013). In this study, D encompasses factors capable of altering the entire agroecosystem and changing the land use pattern in rural China. Environmental pressures accumulate through these socio-economic drivers and could be exacerbated by natural system variability (Mangi et al., 2007). Pressure (P) is the direct and quantifiable effect of D on the rural socio-ecological system, potentially leading to system perturbations and

Table 1. The index system of agriculture sustainable development performance assessment and measurement method.

Criterion	Code	Indicator	Indexes	Attribute	Calculation method	Unit	Data Source	Composite Weight (%)
Drivers	D1	Urbanization	Population Urbanization	–	Urban permanent population / Total population	%	SYBD	0.455
	D2		Economic Urbanization	+	The GDP of the secondary and tertiary industries / GDP	%	SYBD	1.919
	D3		Land Urbanization	–	Construction land area / Administration area	%	CLUD	0.562
	D4	Aggregate Growth Metrics	Population Growth	–	Σ [(Ending Population-Starting Population) / Starting Population] *	%	SYBD	0.696
	D5		Economic Growth	+	Σ [(Ending GDP - Starting GDP) / Starting GDP] *	%	SYBD	3.357
Pressure	P1	Resource Use Pressure	Energy Consumption Efficiency	-	Agricultural electricity consumption / Total output value of agriculture, forestry, animal husbandry and fishery	kWh/ yuan	SYBD	0.649
	P2		Rural Labour Intensity	+	Number of Rural labour force / Agriculture land Area	person/ ha	SYBD; CLUD	0.943
	P3		Cropland Availability for Rural Residents	+	Cropland area / Total rural population	ha/ person	CLUD; SYBD	1.151
	P4		Agricultural Water Demand Pressure	-	Agricultural water consumption / Total output value of agriculture, forestry, animal husbandry and fishery	m^3/ yuan	DWRB; SYBD	0.775
	P5	Land Suitability for Agriculture	Good-quality Cropland	+	Area of superior and high-quality cropland land /Cropland land area	%	CLUD	3.564
	P6		Geographical Composition	+	Area of 'Bazi'/ Administrative area	%	CLUD; SYBD	3.265
	P7	Agricultural Production environment	Fertilizer Application Intensity	-	Agricultural fertilizer application/Agricultural land area	Tons/ha	SYBD; CLUD	0.564
	P8		Pesticide Use Intensity	-	Pesticide use/ Agricultural land area	Tons/ha	SYBD; CLUD	0.536
	P9		Plastic Film Use Intensity	-	Agricultural plastic film/ Agricultural land area	Tons/ha	SYBD; CLUD	1.236
	P10		Diesel Use Intensity	-	Agricultural diesel use/ Agricultural land area	Tons/ha	SYBD; CLUD	0.984
State	S1	Sustainable production capacity	Economic Efficiency of Agricultural Land	+	Added value of agriculture, forestry, animal husbandry and fishery / Total agricultural land area	Yuan/ ha	SYBD; CLUD	1.999
	S2		Average Economic Output of Agriculture	+	Gross output value of agriculture, forestry, animal husbandry and fishery / Rural population	yuan/ person	SYBD	2.636
	S3		Crop Diversity Index	+	-Σpi ln(pi), 'pi' represents the proportion of the sown area dedicated to each crop type.	\	SYBD	0.774
	S4	Ecological Environment	Non-agricultural Grassland Coverage	+	Non-agricultural grassland area/Administrative area	%	CLUD; SYBD	5.074
	S5		Wetland Coverage	+	Wetland area/ Administrative area	%	CLUD; SYBD	4.911

(*Continued*)

Table 1. Continued.

Criterion	Code	Indicator	Indexes	Attribute	Calculation method	Unit	Data Source	Composite Weight (%)
	S6		Forest Coverage	+	Forest area/Administrative area	%	CLUD; SYBD	2.921
Impact	I1	Food Security	Stability of Grain Yield	+	Σ [(Ending grain yield - Starting grain yield) / Starting grain yield] *	%	SYBD	0.517
	I2		Self-sufficient Grain Accessibility	+	Grain yield/ Total population	Tons/ person	SYBD	0.874
	I3		Efficiency of Grain Yield	+	Grain yield/ Grain-sown area	Tons/ha	SYBD	4.986
	I4	Rural-Urban Disparity	Tendency to Abandon Agriculture	+	Σ [(Final rural labour force – Initial rural labour force) /Initial rural labour force] *	%	SYBD	3.323
	I5		Income Disparity	-	Rural disposable income/ Urban disposable income	%	SYBD	3.356
Response	R1	Agricultural Modernization	Mechanization Availability	+	Power of agricultural machinery/Agricultural land area	kw/ha	SYBD; CLUD	4.402
	R2		Efficiency of Irrigation Systems	+	Effective irrigation area/ Agricultural land area	%	SYBD; CLUD	3.95
	R3	Social Services	Educational Attainment	+	Number of graduates from higher and secondary schools/ Total population	%	SYBD	5.857
	R4		Healthcare Services Availability	+	Health technicians/Total population	%	SYBD	21.371
	R5		Highway Density	+	Total Mileage of Opened Highways/Administration area	km/ha	SYBD	4.364
	R6	Social Welfare	Reach of Government's Minimum Subsistence Guarantee	-	Number of rural residents in special poverty receiving special assistance/Rural population	%	SYBD	4.403
	R7		Agricultural Budget Allocation	+	Agriculture, forestry and water expenditure/Public finance budget expenditure	%	SYBD	3.627

The indexes marked with an asterisk (*) utilize data from 2015 to 2021 to calculate cumulative changes, while those without an asterisk only use data from 2021.
For the data required to calculate cumulative change rates, the final/ending year is 2021, and the initial/starting year is 2015.

Abbreviation: SYBD (Statistical Yearbook of Dali); DWRB (Dali Water Resource Bulletin); CLUD (county-level land use data of Dali).
The conversion rate from Chinese Yuan (CNY) to United States Dollars (USD) is approximately 50 CNY = 6.94595 USD on 21 January 2024.

agricultural sustainability challenges (Pinto et al., 2013). State (S) describes observable changes in agricultural ecological dynamics, with system conditions susceptible to alterations caused by P (Pullanikkatil et al., 2016). Impact (I) represents discrete changes in assessing social benefit values related to environmental conditions (Mangi et al., 2007), such as a decline in per capita food possession due to reduced arable land. I can be either positive or negative (Pullanikkatil et al., 2016). This paper analysed the impacts of agricultural land use change on agriculture sustainability. Response (R) is human reactions to perceived change and challenges posed by land use change, addressing P or promoting sustainable agricultural development (Pullanikkatil et al., 2016). R includes laws, policies, regulations, local actions and other measures (Binimelis et al., 2009; Yu et al., 2020). R is described as institutional responses to changes in the system, primarily driven by changes in S and I (Mangi et al., 2007).

2.2.2 Research methods

The weight determination method in this study combines subjective (analytic hierarchy process) and objective (entropy method) approaches.

The analytic hierarchy process (AHP) is a widely used decision-making technique developed by Professor Thomas Saaty in the 1970s (Dos Santos et al., 2019). AHP, as a multi-criteria decision-making method, converts qualitative judgments into

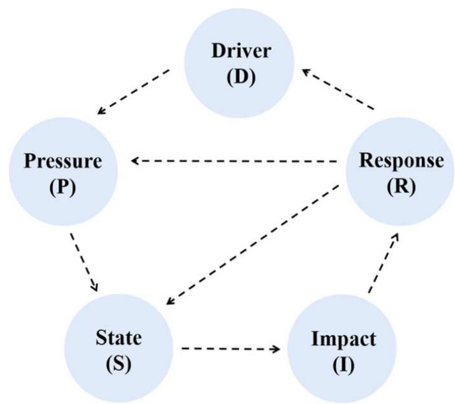

Figure 3. The DPSIR analysis framework. Adapted from Atkins et al. (2011), Mangi et al. (2007), Pullanikkatil et al. (2016), Svarstad et al. (2008), Yu et al. (2020).

numerical values by conducting pairwise comparisons grounded in individual preferences and valuations of the criteria's relative importance (Dos Santos et al., 2019; Saaty, 2006). AHP was adopted in this research to assess the importance and priorities of 33 indexes influencing agricultural sustainable development. From 28 July to 1 August 2023, 14 experts in agriculture or rural development-related fields were invited to provide judgments, including rural and agriculture-related government workers (related to farmland irrigation, land and resources management, and rural tourism), professionals involved in the National Rural Poverty Alleviation projects, scholars from Southwest China and other stakeholders. The 1–9 Linear Scale developed by Saaty (1990) was chosen as the criterion for relative importance valuation. A consistency test on the judgment matrix is necessary given the complexity and diversity of research questions and assessed objects; the test is successful if the obtained consistency ratio (CR) value is less than 0.1, otherwise, adjustments are needed (Franek & Kresta, 2014).

The entropy-weighted method, an objective assignment method (Lin & Hou, 2023), utilizes entropy to measure the uncertainty degree of a system, determining the relative importance of comparative indicators or the objective weight of the indicator system (Geng et al., 2021). Weights are calculated based on attribute dispersion and indicators statistics (Lin & Hou, 2023). The index values are categorized into positive ('the bigger, the better') and negative ('the smaller, the better') indexes according to the assessment goal. To eliminate the influence of dimension and order differences, standardization of all variables is necessary, ensuring values fall within a comparable range, typically between 0 and 1.

Composite weight. While the AHP considers expert experience and decision maker's preferences, resulting in a rational yet somewhat subjective ranking, the entropy weight method provides objective weights by fully exploring original data (Guangdong et al., 2017; Nyimbili & Erden, 2020). To enhance reliability and validity, it is necessary to integrate the subjectivity of AHP and the objectivity of the entropy weight method (Guangdong et al., 2017). The combined AHP-entropy weights method has gained popularity across various fields for obtaining more scientific and comprehensive weights (Bai et al., 2018; Guangdong et al., 2017; Nyimbili & Erden, 2020). By combining the subjective weight Z_i from the AHP and the objective weight W_i from the Entropy method, the combined weight X_i can be calculated using the following equation:

$$X_i = \frac{Z_i W_i}{\sum_{j=1}^{n} Z_i W_i}, \ (j = 1, 2, \ \ldots, n)$$

2.2.3 Data source

The county-level land use data for this study were obtained from the Institute of Land and Resources Planning and Design of Yunnan Province. As of 2024, China has completed three national land surveys. The first survey started in 1984 and finished in 1997. The second survey began in 2007 and concluded in 2009. The third survey was initiated in 2019 and was finished in 2021. The differing land classifications employed in these three national land surveys make it impractical to compare changes in land use between 2021 and the preceding years. The land use category data used in this study are from the Third National Land Survey, which involved 219,000 surveyors collecting data from 295 million survey plots and established a national land survey database covering four administrative levels in China: national, provincial, municipal, and county levels.

Socioeconomic datafrom the Statistics Bureau of Dali Bai Autonomous Prefecture and Dali Bai Autonomous Prefecture Water Affairs Bureau included information from statistical yearbooks such as the Statistical Yearbook of Dali and Dali Water Resource Bulletin. However, due to limitations in data availability, only data as early as 2015 could be obtained when measuring cumulative changes.

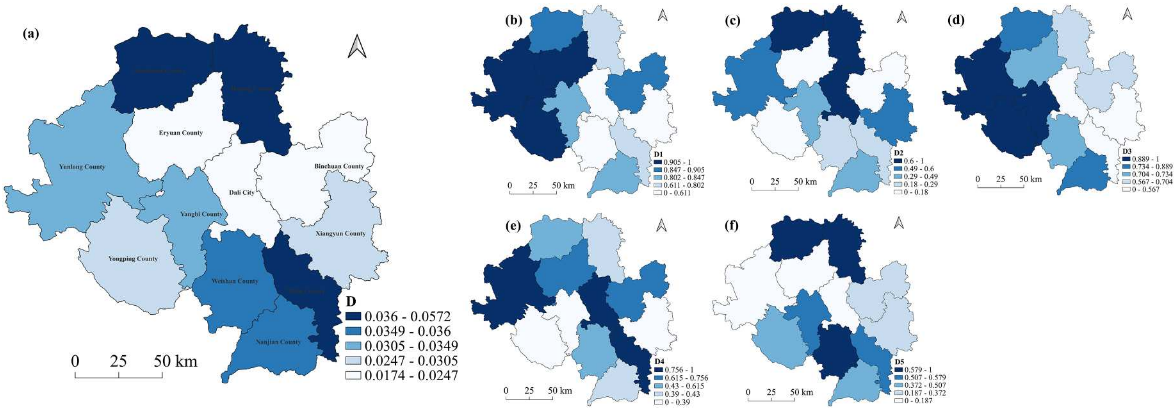

Figure 4. Performance of Drivers in Dali Prefecture. (a) Driver Indicator; (b) Population Urbanization; (c) Economic Urbanization; (d) Land Urbanization; (e) Population Growth; (f) Economic Growth.

3. Results

3.1. Performance of agricultural sustainable development

Dali Prefecture's D performance ranged from 1.742% to 5.721%, with a mean value of 3.324%. The pattern revealed higher values in the north and south and lower values in the central and eastern part (Figure 4(a)). The land urbanization index (Figure 4(d)) exhibited a similar pattern to the population urbanization index (Figure 4(b)), with lower scores in the west and higher scores in the east. Dali City, Midu County, and Xiangyun County had a higher proportion of construction land and urban residents, indicating a potential shortage of land and labour resources for agricultural development compared to other regions.

The P performance varied from 4.696% to 11.168%, with a mean value of 6.005%, showing a spatial pattern of high values in the central part and low values in the west (Figure 5(a)). Regions with high P scores generally exhibited high labour intensity (Figure 5(c)), a substantial proportion of good-quality cropland (Figure 5(f)) or an efficient fertilizer use pattern (Figure 5(h)). Nanjian and Weishan counties showed high resource use efficiency in energy consumption (Figure 5(b)) and agricultural water demand (Figure 5(e)), while Heqing may face potential waste issues in both indexes. Areas with higher population urbanization (Figure 4(b)) tended to have a less sufficient rural labour force (Figure 5(c)). Despite having high-quality cropland (Figure 5(f)), and more flat land suitable for farming (Figure 5(g)), Dali City, Binchuan County, Xiangyun County, and Midu County had very small per capita cropland owned by rural population (Figure 5(d)). Xiangyun, Binchuan, Heqing and Nanjian counties showed an overuse of fertilizer (Figure 5(h)) and pesticide (Figure 5(i)), while Xiangyun and Midu counties used plastic film (Figure 5(j)) and diesel (Figure 5(k)) inefficiently. Notably, there was a significant difference in the scores for plastic film use intensity (Figure 5(j)) and diesel use intensity (Figure 5(k)), indicating serious overuse in Midu and Xiangyun counties.

The performance for S ranged from 4.689% to 13.404%, with a mean value of 6.453%, showing a spatial pattern of high in the north and low in the southwest (Figure 6(a)). The economic efficiency of agricultural land decreased from southeast to northwest (Figure 6(b)), sharing a similar distribution pattern with labour intensity (Figure 5(c)) and geographical composition (Figure 5(g)). Midu, Xiangyun, and Binchuan counties demonstrated better efficiency in using land resources to generate economic output (Figure 6(b)), with Binchuan and Midu also having the highest per capita agricultural economic output (Figure 6(c)). Xiangyun, Nanjian, and Yunlong counties exhibited the most diverse and abundant crop cultivation patterns (Figure 6(d)), while Yangbi, Binchuan, and Heqing counties demonstrated relatively lower crop diversity. The spatial pattern for non-agricultural grassland showed higher value in the north and lower in the south (Figure 6(e)). The northwest of Dali, including Jianchuan County and Yunlong County, had high forest coverage (Figure 6(g)). Erhai is an alpine fault lake in Dali City, covering 25,000 hectares, with a catchment area of about 256,500 hectares (Zhao et al., 2021). The

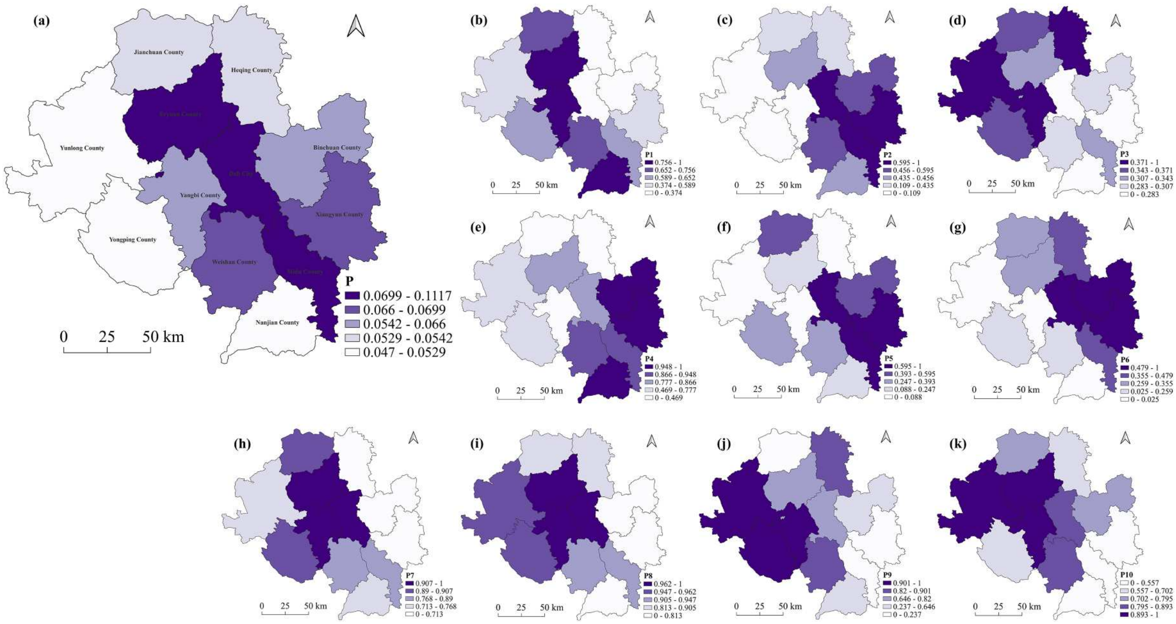

Figure 5. Performance of Pressure in Dali Prefecture. (a) Pressure indicator; (b) Energy consumption Efficiency; (c) Rural labour intensity; (d) Cropland availability for rural residents; (e) Agricultural water demand pressure; (f) Good-quality cropland; (g) Geographical composition; (h) Intensity of fertilizer application; (i) Intensity of Pesticide use; (j) Intensity of Plastic film use; (k) Intensity of diesel use.

presence of Erhai Lake contributes to relatively abundant wetland coverage in Dali City, Eryuan County and Jianchuan County (Figure 6(f)). Regarding the ecological environment, only Jianchuan County had a high coverage rate of forests, non-agricultural grasslands and wetlands in Dali Prefecture.

The performance for I ranged from 4.727% to 9.857%, with a mean value of 6.589%, with a spatial pattern showing higher values in the southeast and lower in the west (Figure 7(a)). According to raw data without normalization (Table 2), only six counties showed an increasing trend in cumulative grain production capacity (I1) over the past six years (Figure 7(b)). Among them, Yunlong, Yongping, and Yangbi counties not only have stable grain production capacity (Figure 7(b)), but also sufficient per capita food self-sufficiency (Figure 7(c)). However, Dali City's production of self-sufficient food for its people was limited, and its grain output continued to decline.

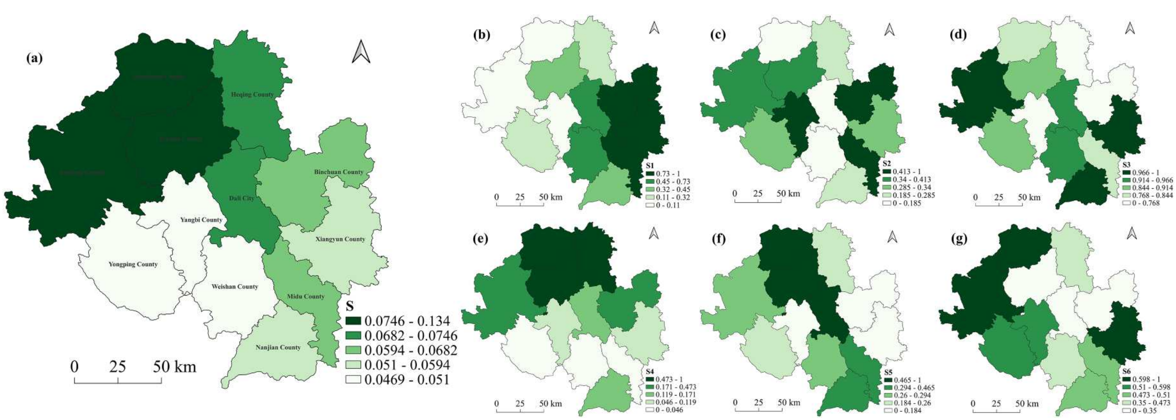

Figure 6. Performance of State in Dali Prefecture. (a) State Indicator; (b) Economic Efficiency of Agricultural Land; (c) Average Economic Output of Agriculture; (d) Crop Diversity Index; (e) Non-agricultural Grassland coverage; (f) Wetland Coverage; (g) Forest coverage.

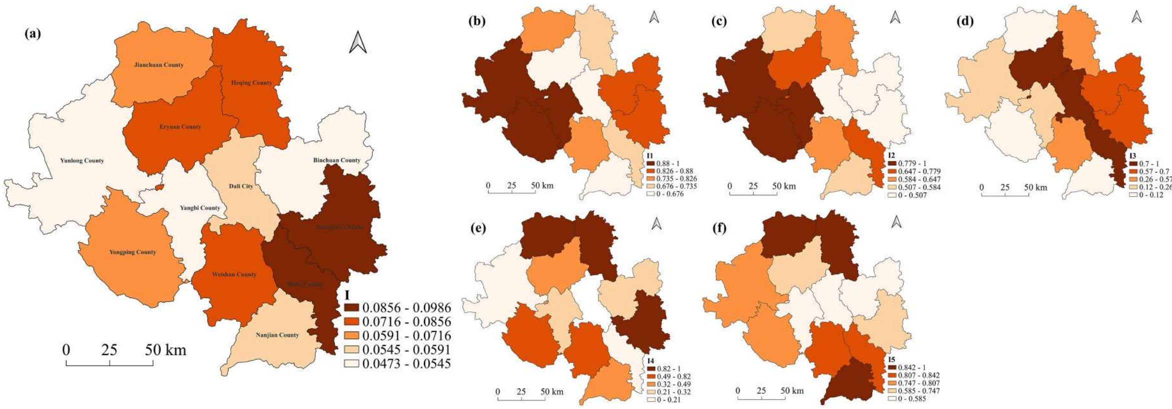

Figure 7. Performance of Impact in Dali Prefecture. (a) Impact Indicator; (b) Stability of grain yield; (c) Accessibility of self-sufficient grain; (d) Efficiency of grain yield; (e) Tendency to abandon agriculture; (f) Income disparity.

The efficiency of grain production varies widely in different regions of Dali Prefecture (Figure 7(d)). The top three most efficient areas – Dali city, Eryuan county and Midu county – scored higher than 0.7, while the three least efficient areas – Jianchuan county, Yongping county and Nanjian county – scored lower than 0.12. The pattern of the tendency to abandon agriculture (Figure 7(e)) is opposite to the pattern of population growth (Figure 4(e)). In regions with higher population growth, such as Dali city, Midu and Yunlong counties, there is a greater proportion of farmers abandoning agriculture for other industries. Notably, among the 12 regions, only two, Dali City and Midu County, have a negative cumulative change rate of the rural labour force (I4) in 6 years (Table 2). The relatively small income disparity between urban and rural areas (Figure 7(f)) may contribute to the low tendency of farmers in Jianchuan and Heqing counties to abandon agriculture as a livelihood.

The performance for R ranged from 5.286% to 40.286%, with a mean value of 15.582%, showing a spatial pattern of higher values in the east and lower in the west (Figure 8(a)). The distribution patterns of mechanization availability (Figure 8(b)) were like the pattern of irrigation system efficiency (Figure 8(c)), with high-scoring areas concentrated in the central and eastern regions, and low-scoring areas in the west. Dali City, Midu County, and Binchuan County not only had a high mechanical power density per unit of agricultural land but also a high proportion of agricultural land benefiting from effective irrigation practices. Referring to the agricultural water demand in Yangbi County (Figure 5(e)), the low proportion of effectively irrigated areas may have contributed to the high agricultural water consumption. When measuring educational attainment (Figure 8(d)), healthcare services availability (Figure 8(e)) and highway density (Figure 8(f)), Yunlong County scored low on these three social service indexes. The proportion of high school graduates in Yangbi County, Yunlong County, and Midu County was relatively low (Figure 11(d)). However, when examining the allocation of public fiscal expenditure in these three counties, 'education' is prioritized as either the second or first priority in their budgets (Table 3). Eryuan, Yunlong, and Heqing counties had relatively low availability of healthcare services, but the response from their respective county governments was positive, as healthcare was given high priority in the allocation of public fiscal expenditures. Notably, 'healthcare' was listed as the top priority in Eryuan, while Yunlong and Heqing ranked it fourth and third, respectively.

Table 2. Part of the raw data (Unit:%).

	DL	YB	XY	BC	MD	NJ	WS	YP	YL	EY	JC	HQ
I1	−49.953	5.430	3.329	5.389	−3.921	−8.001	0.080	6.999	12.994	−11.548	−3.315	−4.857
I4	−1.849	1.810	24.639	2.436	−3.322	2.486	8.287	9.772	−7.835	8.033	21.321	21.009

Abbreviations: DL (Dali City); YB (Yangbi County); XY (Xiangyun County); BC (Binchuan County); MD (Midu County); NJ (Nanjian County); WS (Weishan County); YP (Yongping County); YL (Yunlong County); EY(Eryuan County); JC(Jianchuan County); HQ(Heqing County).

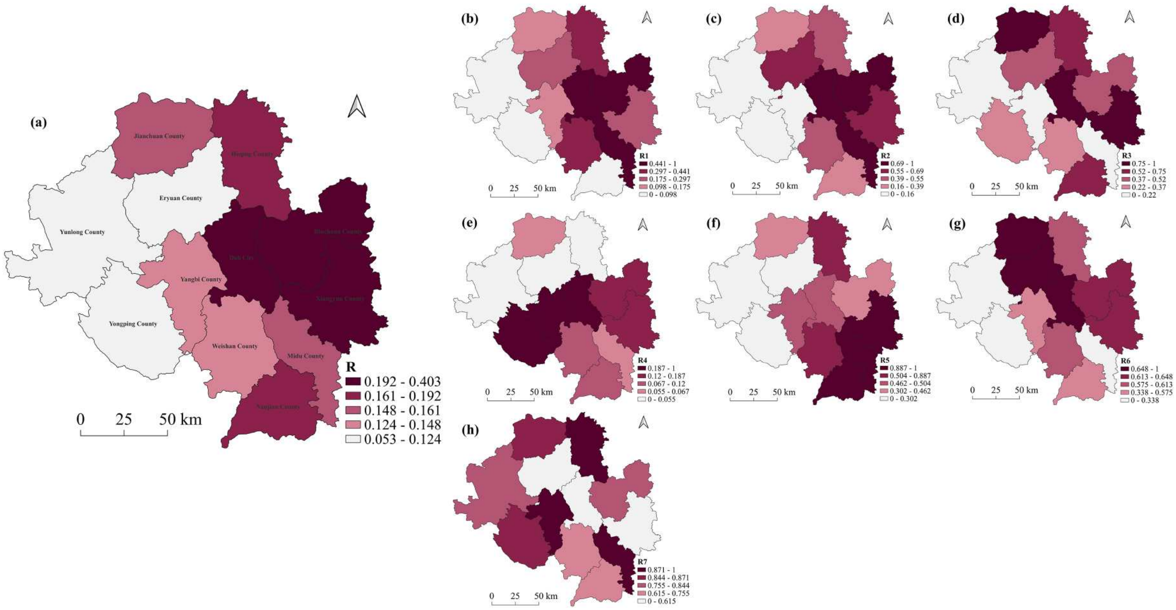

Figure 8. Performance of Response in Dali Prefecture. (a) Response indicator; (b) Mechanization availability; (c) Efficiency of irrigation system; (d) Educational attainment; (e) Healthcare services availability; (f) Highway Density; (g) Reach of government's minimum subsistence guarantee; (h) Agricultural budget allocation.

Table 3. Ranking of Dali Prefecture's 2021 public fiscal expenditure items.

	DL	YB	XY	BC	MD	NJ	WS	YP	YL	EY	JC	HQ
Public service	6	5	6	5	5	5	5	6	5	5	5	5
Public Safety	8	7	8	6	6	6	7	8	7	7	9	8
Education	1	2	1	1	1	1	2	2	2	3	2	1
Science & technology	12	14	13	11	12	12	9	14	13	11	13	13
Culture, Tourism, Sports and Media	10	9	9	10	9	9	10	11	10	9	8	11
Social Security and Employment	5	3	2	4	3	3	4	3	3	2	3	4
Healthcare	4	4	4	3	4	4	1	4	4	1	4	3
Energy Conservation & Environmental Protection	9	10	11	12	7	10	12	12	8	8	10	9
Urban & Rural Community	2	8	7	8	10	8	8	7	9	10	7	7
Agriculture, forestry and water	7	1	3	2	2	2	3	1	1	4	1	2
Transportation	11	11	10	9	11	11	11	10	11	12	11	10
Business and Service Industries	14	13	12	13	13	14	13	9	14	13	14	12
National Defense	13	12	14	14	14	13	14	13	12	14	12	14
Other	3	6	5	7	8	7	6	5	6	6	6	6

Source: The Statistical Yearbook of Dali 2022.

Regarding highway density (Figure 8(f)), Nanjian, Midu and Xiangyun counties exhibited a denser highway network as they are located on the essential route from Dali Prefecture to Chuxiong Prefecture, Pu'er City and Lijiang City. Yunlong and Yongping counties have low road density due to their steep terrain and extensive mountainous areas, making road construction challenging. Yunlong, Yongping and Midu were the three counties with the lowest scores in the government's minimum subsistence guarantee reach index, indicating that a significant number of rural residents in these counties rely on government's subsistence allowance for survival (Figure 8(g)). In response criterion, Yunlong and Yongping counties consistently received low scores, with Yunlong scoring the lowest in six indexes and Yongping scoring the lowest in four indexes, indicating their poor performance in meeting the response criterion.

The agricultural sustainable development index in Dali Prefecture in 2022 ranges from 25.653% to 66.807%, with a mean value of 40.993%. Higher

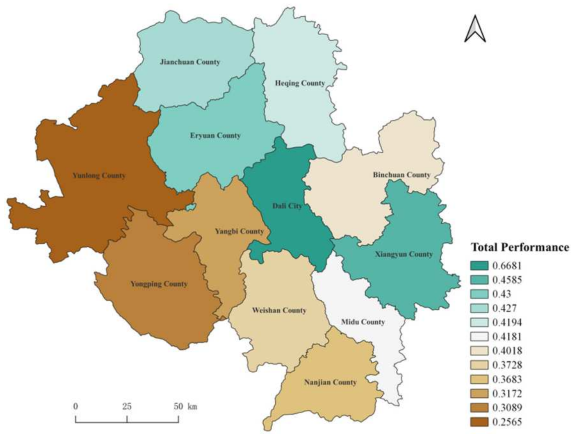

Figure 9. The overall performance at the county level of Dali Prefecture.

values were observed in the central and northeast areas, while lower values were concentrated in the west and southwest (Figure 9). Dali City, the capital of Dali Prefecture, had significantly better sustainability, being 1.46 times that of second-ranked Xiangyun County and 2.6 times that of last-ranked Yunlong County. If 0.5 is considered the passing threshold for this agricultural sustainability assessment, only Dali City has passed the test.

Figure 10 displays the scores of each index in each county and city, with a mostly red left half and a mostly blue right half. The deeper the red, the higher the score for the corresponding index in that county or city; the deeper the blue, the lower the score for the corresponding index. Most counties and city showed relatively sustainable performance in intensity of plastic film use (P9), intensity of diesel use (P10), population growth (D4), agricultural water demand pressure (P4), crop diversity (S3), intensity of fertilizer application (P7), intensity of pesticide use (P8), energy consumption efficiency (P1), income disparity (I5), land urbanization (D3), accessibility of self-sufficient grain (I2), population urbanization (D1), agricultural budget allocation (R7). However, in categories such as average economic output of agriculture (S2), cropland availability for rural residents (P3), wetland coverage (S5), non-agricultural grassland coverage (S4), reach of government's minimum subsistence guarantee (R6), educational attainment (R3), economic urbanization (D2), healthcare services availability (R4), good-quality cropland (P5), rural labour intensity (P2), mechanization availability (R1), geographical composition (P6), efficiency of irrigation systems (R2), and economic efficiency of agricultural land (S1), the performance of most counties and cities was not sustainable enough.

For the Response criterion, five indexes received low scores throughout the entire prefecture, with only one index achieving high scores among the counties and city. According to (Hu et al., 2022),

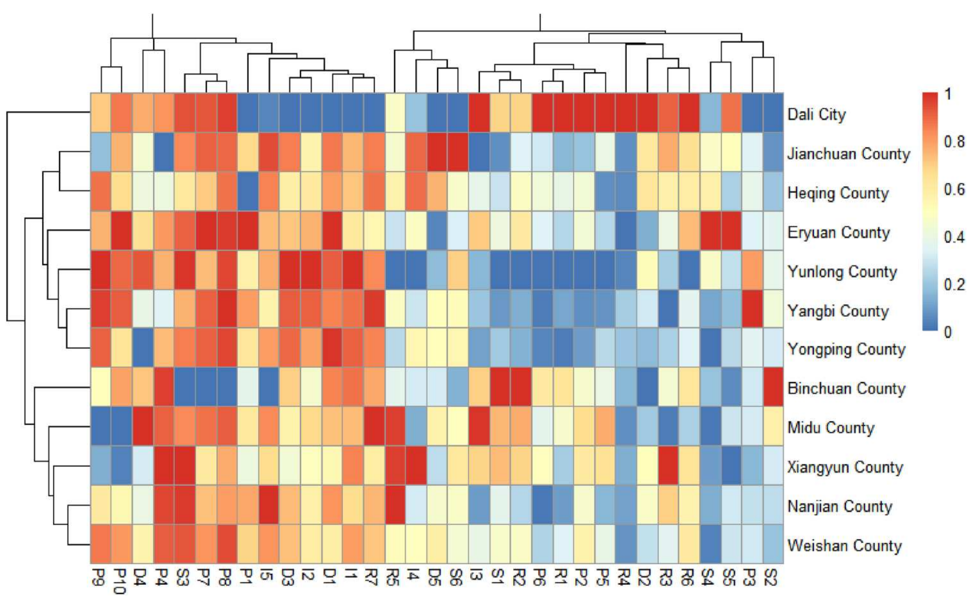

Figure 10. Performance at the county level for each index.

'Farmers' well-being lagged agricultural production and rural environment in most of BTH'. This study echoes Hu's findings to some extent. Indeed, farmers' well-being is lagging: indexes such as Educational Attainment (R3), Reach of Government's Minimum Subsistence Guarantee (R6), and Healthcare Services Availability (R4) performed poorly across the prefecture. Among the five indexes of social service and social welfare, only Agricultural Budget Allocation (R7) received a high score. The findings indicate that the agricultural production environment in Dali Prefecture presented a relative level of sustainability. For example, indexes such as Pesticide Use Intensity (P9), Diesel Use Intensity (P10), Fertilizer Application Intensity (P7), and Pesticide Use Intensity (P8) are generally low. Judging by the scores, it's evident that Dali Prefecture's geographical conditions (P6) offer farmers unfavorable farming environments and low-quality farmland (P5). Moreover, the prevalence of mountainous terrain further diminishes the likelihood of local farmers employing agricultural machinery (R1) for farming.

Through the analysis of the agricultural sustainability index of all the counties and city in Dali Prefecture, the scores systematically illustrate the challenges and comparative advantages each region faces in terms of agricultural sustainability across 33 indexes. This information could serve as a guide for local governments in formulating specific interventions and measures for promoting sustainable agricultural development at the county level.

3.2. The index assessment system

Based on the weights assigned to the five criteria, their contribution to agricultural sustainability was ranked as follows: Response > State > Pressure > Impact > Driver (Table 4). The Response criterion not only held the top position but also had a score ratio 2.62 times greater than the second-ranking criterion. Meanwhile, the top ten index rankings (Table 5) included all seven indexes related to the Response criterion. This emphasizes the significant role of Response in promoting agricultural sustainable development, while the Driver criterion has a relatively lower impact on agriculture sustainability.

In Figure 11, Response made up a significant part of the score structure in all regions except Yunlong County. Yunlong County received a low score mainly because it lacked sufficient Response measures to promote sustainable agricultural development. Conversely, Dali City's response score comprised nearly 60% of its total score, which explains why Dali City's overall score surpassed that of other counties. Dali City's high Response contribution was attributed to factors such as high mechanization availability, efficient irrigation, high education levels, and ample medical services.

Notably, the two drivers that initiated this study – land use change (land urbanization) and population urbanization – had the least impact on sustainable agricultural development. This suggests that while certain drivers can induce changes with negative effects, they aren't the most critical factors that render the system unsustainable. Effective responses by governments and stakeholders are crucial for advancing agricultural sustainability.

Except for the Driver force, where there's minimal difference in ranking between subjective and objective weights, there are significant disparities in the ranking of subjective and objective weights for Pressure, State, Impact, and Response (Table 6). Out of 33 indexes, 11 exhibit a difference of 15 ranks between subjective and objective rankings. AHP derives weights through pairwise comparisons, while the entropy weighting method directly utilizes the statistical properties of the data. This disparity in

Table 4. Composite weight for criteria.

Criterion	Weight (%)	Ranking
Driver	6.988	5
Pressure	13.668	3
State	18.315	2
Impact	13.056	4
Response	47.973	1
Sum	100	\

Table 5. Top ten and bottom five indexes in composite weight ranking.

Criteria	Code	Indexes	Ranking
Response	R4	Healthcare services availability	1
Response	R3	Educational attainment	2
State	S4	Non-agricultural grassland coverage	3
Impact	I3	Efficiency of grain yield	4
State	S5	Wetland coverage	5
Response	R6	Reach of government's minimum subsistence guarantee	6
Response	R1	Mechanization availability	7
Response	R5	Highway density	8
Response	R2	Efficiency of irrigation systems	9
Response	R7	Agricultural budget allocation	10
Pressure	P7	Intensity of fertilizer application	29
Driver	D3	Land urbanization	30
Pressure	P8	Intensity of pesticide use	31
Impact	I1	Stability of grain yield	32
Driver	D1	Population urbanization	33

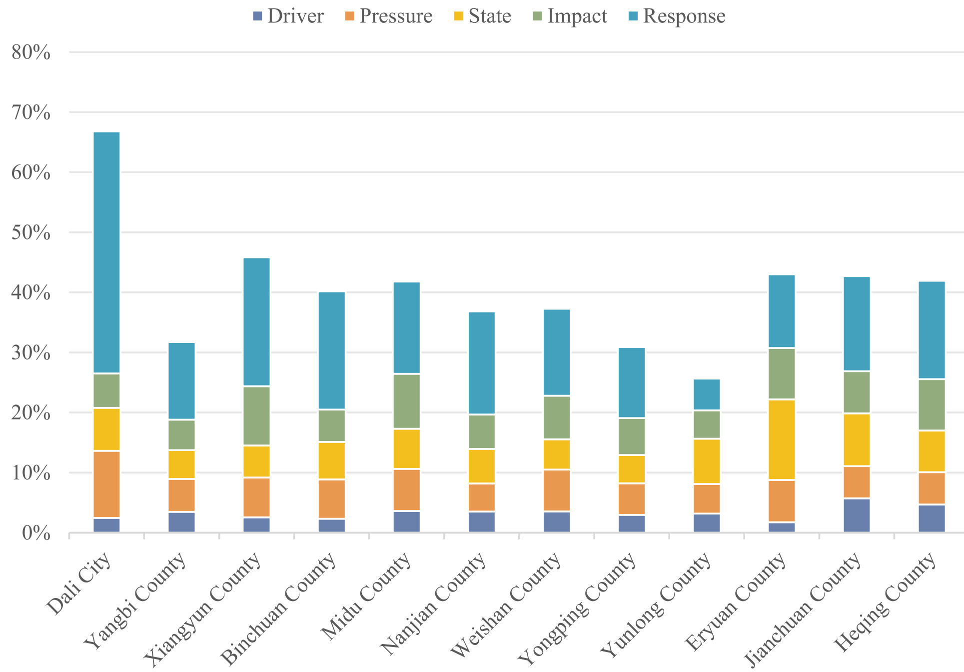

Figure 11. The agricultural sustainability score of Dali Prefecture and the scoring ratio of the indicator layer.

methodology could result in inconsistencies between the weights obtained by the two methods.

Among them, indexes experts perceive as unimportant based on their personal experience, knowledge, and preferences, while data indicates their significance are Energy Consumption Efficiency (P1), Rural Labour Intensity (P2), Cropland Availability for Rural Residents(P3), Good-quality Cropland(P5), Geographical Composition(P6), Economic Efficiency of Agricultural Land (S1), Non-agricultural Grassland Coverage (S4), and Mechanization Availability (R1). Notably, these indicators are closely related to land resources and cultivation. These indexes are largely associated with land resources and farming activities. Moreover, indexes such as Crop Diversity (S3), Forest Coverage (S6), Income Disparity (I5), Highway Density (R5), Reach of Government's Minimum Subsistence Guarantee (R6), Agricultural Budget Allocation (R7), and Pesticide Use Intensity (P8) are deeming as unimportant by the data but important by experts. These indexes are more closely related to 'social' factors such as social welfare, public infrastructure, and economic development. This suggested that experts tend to prioritize factors concerning farmers' livelihoods and working environments when assessing agricultural sustainability, drawing from their personal experiences and knowledge. Meanwhile, the statistics tend to highlight factors directly linked to agricultural activities.

4. Discussion

4.1. Implication of the agricultural sustainability performance

Rapid urbanization and the rise in non-agricultural employment opportunities have attracted more and more younger and middle-aged rural labourers, causing challenges for the agricultural sector, such as rapid aging and labour shortage (Liu et al., 2023). Rural labourers' out-migration has led to a continuous sharp reduction in farmland utilization, which has led to a corresponding sharp decline in grain production (Li et al., 2017; You, 2016). Farmers therefore increase the use of agricultural energy and agrochemical to boost land productivity (Wang et al., 2014; You et al., 2018). In addition to threatening environmental sustainability, overuse of fertilizers is well recognized as a harm to the long-term sustainability of crop production (Zulfiqar & Thapa, 2017). As the country with the largest population in the world but limited arable land per capita, China uses more chemical fertilizers

Table 6. Weight and ranking for 33 indexes.

	Subjective		Objective		Composite	
Index	Weight (%)	Ranking	Weight (%)	Ranking	Weight (%)	Ranking
D1	1.124	31	1.344	28	0.455	33
D2	2.055	18	3.102	14	1.919	19
D3	1.276	29	1.462	27	0.562	30
D4	1.152	30	2.008	23	0.696	27
D5	3.406	12	3.275	12	3.357	12
P1	0.773	33	2.790	17	0.649	28
P2	0.887	32	3.532	10	0.943	23
P3	1.291	28	2.961	16	1.151	21
P4	1.538	23	1.674	25	0.775	25
P5	2.680	14	4.418	5	3.564	11
P6	1.925	20	5.636	3	3.265	14
P7	1.482	25	1.264	30	0.564	29
P8	1.514	24	1.177	33	0.536	31
P9	1.588	22	2.587	18	1.236	20
P10	1.407	26	2.325	20	0.984	22
S1	1.710	21	3.884	8	1.999	18
S2	2.541	15	3.447	11	2.636	17
S3	2.065	17	1.245	32	0.774	26
S4	2.462	16	6.849	2	5.074	3
S5	3.867	10	4.219	7	4.911	5
S6	4.496	7	2.159	22	2.921	16
I1	1.358	27	1.264	31	0.517	32
I2	1.930	19	1.505	26	0.874	24
I3	3.904	9	4.244	6	4.986	4
I4	3.435	11	3.214	13	3.323	15
I5	4.921	6	2.266	21	3.356	13
R1	2.847	13	5.136	4	4.402	7
R2	4.342	8	3.022	15	3.950	9
R3	5.398	5	3.605	9	5.857	2
R4	8.218	2	8.640	1	21.371	1
R5	5.938	4	2.442	19	4.364	8
R6	7.419	3	1.972	24	4.403	6
R7	9.051	1	1.331	29	3.627	10
Sum	100	\	100	\	100	\

than any other country to increase arable land productivity (Huang et al., 2017). Also, China is the world's primary consumer and producer of chemical pesticides, using 1.5–4 times the global average per hectare, with over 10% of its farmland suffering from pesticide contamination (Zhang & Zhang, 2024). Pesticides pose health risks to farmers and consumers, causing various acute and chronic effects based on exposure levels, while organic farming provides a viable solution to mitigate these risks and promote sustainable agriculture (Sapbamrer & Thammachai, 2021). The average amount of pesticide application per unit of cultivated land in the country was 3.57–5.68 times the world average from 1995 to 2018 (Li et al., 2021). While pesticides are effective in controlling pests and diseases, chemical residues caused by excessive use of pesticides can have potential negative impacts on the environment, human health and biodiversity (Hüesker & Lepenies, 2022; Li et al., 2021). However, controlling the use of fertilizers and pesticides is challenging, as insufficient use may reduce yields and farmers' incomes (You, 2016). Based on cases from Europe, South Africa, USA and Nigeria, it is evident that younger farmers have higher education, understand innovative technologies, are knowledgeable about organic farming practices, and have access to information on organic farming are more likely to adopt organic agriculture (Mishra et al., 2018; Mugivhisa et al., 2017; Oluwatosin, 2020; Serebrennikov et al., 2020). However, Mugivhisa et al. (2017) and Serebrennikov et al. (2020) also found that while education can benefit farmers, excessive education may lower their inclination to adopt organic farming practices in Europe, and individuals with higher levels of formal education prioritize their professions over farming in South Africa. This study has not yet found a direct link between Pesticide Use Intensity (P8) and Fertilizer Application Intensity (P7) with Educational Attainment (R3), possibly due to multiple factors influencing the adoption of organic agriculture. Regardless of education level, from the case of Kentucky in the USA, perceived cognitive and knowledge barriers among farmers are the primary obstacles preventing their adoption of organic farming practices (Mishra et al., 2018). Additionally, (Mishra et al., 2018) found that a lack of understanding of organic agriculture, such as its profitability and proficiency level and skill requirements of labourers, can deter farmers from attempting organic farming in Kentucky. Similarly, Mugivhisa et al. (2017) observed the positive role 'descendants' play in farmers' adoption of conservation agriculture in Europe. All these studies emphasize the significance of effective extension activities and training for farmers to improve their understanding of organic agriculture, advocating for active engagement from stakeholders such as local governments. Meanwhile, projects aimed at promoting organic agriculture should be customized based on affordability, teachability, risk resistance capacity, farming scale, and crop varieties preferred by local farmers.

Efficient water management is crucial for increasing food production to meet the needs of a growing population, as water security is fundamental to food security (Kang et al., 2017). China, with a large population but limited per capita freshwater resources, faces water shortages due to high agricultural demand, which consumes 80-90% of the country's freshwater (Wang et al., 2019). The issue is worsened by outdated irrigation technology, leading to inefficient water use (Wang et al., 2019). Enhancing the efficiency of agricultural water use is vital for regional food security and ecological sustainability (Cao et al., 2021). Despite the Yangtze, Pearl, and Mekong rivers flowing through Yunnan province, it remains vulnerable to droughts due to uneven water distribution and insufficient water conservation infrastructure (Fan et al., 2021). Data reveals that 43% of meteorological disasters in Yunnan are droughts. In 2019, the drought from April to June affected 1.35 million hectares of crops, including 79,000 hectares of crop failure, resulting in a direct economic loss of 6.562 billion yuan (Ding & Gao, 2020). According to 2018 data from China's National Bureau of Statistics, nearly 60% of crop areas in China lack sufficient water for irrigation (Li et al., 2020). Economic benefits from irrigation go beyond the value of crop yield, extending to the capacity to expand irrigated areas, with irrigated land typically yielding twice as much produce per unit compared to rainfed land (Zhang et al., 2021). From cases of Mali, France, China, Malawi, India, Tajikistan and sub-Saharan Africa, we found better irrigation infrastructure helps farmers access water, enhancing rural livelihoods, farm economic performance, diversifying household and crop quality while also reducing poverty and encouraging the cultivation of high-value cash crops (Li et al., 2020). Data from this study confirms that regions with higher irrigation efficiency (R1) also tend to demonstrate better efficiency in utilizing land resources to generate economic output (S2). Since 2000, drought events have increased in Yunnan with decreasing precipitation, leading to an expansion in drought-affected areas and a shortened occurrence cycle from 2–3 years to 1–2 years (Ding & Gao, 2020). Improving irrigation infrastructure, particularly in drought-affected regions, is crucial for enhancing water access and efficiency, promoting rural economic growth. It should be a priority for local governments.

In the late 1970s, China shifted from a planned to a market economy, allowing rural residents to move to cities (Qin & Liao, 2016). Due to the polarization effect of large cities, the unbalanced distribution of factors like labour, technology, and infrastructure in rural areas caused a decline in rural functions, widening the gap between urban and rural areas (Hu et al., 2022). The big difference in income between urban and rural areas allows cities to provide economic opportunities and resources that are lacking in rural areas. This results in a significant movement of rural labour to urban areas, which harms the sustainable development of agriculture. The number of rural labourers moving to urban areas rose from 72 million in 1996 to 288 million in 2018 (Zhou et al., 2020). In regions with low rural labour intensity (P2), the overall performance and performance for most indexes under Response are not high, such as Mechanization Availability (R1), Efficiency of Irrigation Systems (R2), Educational Attainment (R3), Healthcare Services Availability (R4), and Highway Density (R5), while the local Reach of Government's Minimum Subsistence Guarantee (R6) for these regions is relatively high. The findings align with the study of Zhang and Wang (2024), who noted that rural labourers' willingness to return to their hometowns is affected by perceived benefits and the quality of public services. Local governments should seek eligible funds from the central or provincial government to support agriculture revitalization and strengthen public service in healthcare, education, and transportation while providing subsidies to encourage the return of rural labourers. Meanwhile, the development of secondary and tertiary industries can enhance agricultural efficiency and rural infrastructure (Hu et al., 2022). For example, the thriving tourism sector in Dali City has positively impacted local well-being and infrastructure. Also, governments need to plan and establish a well-connected transportation network to facilitate local agricultural trade and economic activities, as robust transport infrastructure is crucial for fostering growth and development (Banerjee et al., 2020).

From the definition of mountain areas as regions with significant constraints on land utilization or where challenges exist in expanding cultivable land area, according to FAO (2013), it is evident that mountainous terrain raises production costs and limits productivity (Franco et al., 2020). Currently, farm machines are designed for larger parcels of flatlands with greater yield potential (Devkota et al., 2020). Terracing and steep slopes are common features in mountain areas, which restrict or prevent the use of machinery (Franco et al., 2020). In Nepal, mountains cover 24% of the total area, and hills cover 56%. Animals (41%) and humans (36%) remain the primary sources of agricultural power, with approximately 92% of mechanical power available in Nepal concentrated in the Terai Plains region (Devkota et al., 2020). In the hills and mountains of Nepal, only about 8% of farms are mechanized compared to 46% in the Terai plains (Devkota et al., 2020). Mechanization needs to cater to specific requirements tailored for small-scale terraced farming in hilly and mountainous regions like Nepal and Yunnan. For the pattern of Tendency to abandon agriculture (I4), mountainous terrain did not show a significant impact on the migration rate of agricultural labour in Dali prefectures from 2015 to 2021. But this trend corresponds to the pattern of rural labour intensity (P2), where mountainous areas exhibit lower rural labour intensity, as observed in cases from Nepal, Turkey, and China. Hilly areas in Nepal witness the highest rates of out-migration, exacerbating labour shortages in the hills of Nepal (Devkota et al., 2020). In northern Turkey, there was a notable correlation (at the 95% confidence level) between the population decline of forest villages and the slopes and elevations of village locations (Erkan Buğday & Özden, 2017). Based on data from 2014 across 29 provinces or cities in China, labour migration and farmland abandonment were observed to be most common in mountain villages, followed by hilly villages and then plain villages (Xu et al., 2019). Migration may lead to less sustainable farming practices, impacting long-term agricultural productivity and land degradation (Caulfield et al., 2019). The rise in rural out-migration is largely driven by limited job opportunities, the necessity to enhance the sustainability of household livelihoods, and improve resilience to natural disasters like drought and saltwater intrusion and agricultural setbacks (Das, 2015; Tran et al., 2023). To improve farmers' financial stability and living standards, it's essential for the government to customize projects and initiatives based on local characteristics and conditions, as evidenced by successful cases. The rising rural out-migration has been significantly reduced since the implementation of the Mahatma Gandhi National Rural Employment Guarantee Act in India in 2005, which aimed at increasing rural employment opportunities and raising wages in agricultural and non-agricultural sectors (Das, 2015). In Anhui (China), the Ecological Welfare Forest Program has some mitigating effects on rural out-migration by increasing household income and supporting the regeneration of forest resources, potentially improving living conditions and reducing the need for migration (Zhang et al., 2018).

Researchers should prioritize the development of biodegradable plastic film technologies and enhance film recycling efficiency to achieve zero residues. Local governments need to regulate plastic film production and organize regular cleanups of agricultural and rural plastic waste to mitigate environmental risks. Furthermore, local governments can promote energy-smart agriculture practices by subsidizing technologies such as site-specific nutrient management and precision irrigation management (Kakraliya et al., 2022). Energy-smart agriculture not only reduces intensive farming but also decreases diesel demand (Kakraliya et al., 2022). Diesel-powered machinery, while enhancing agricultural efficiency and productivity, poses a significant source of air pollutants, contributing to environmental issues such as global warming and acid rain (Ai et al., 2021). In regions with high water and energy consumption, like Heqing County, local governments can explore the use of cleaner production technologies to lower environmental risks (Hu et al., 2022). Agricultural diversity plays a crucial role in maintaining a healthy ecosystem and promoting sustainable agricultural development (Zulfiqar & Thapa, 2017). Diverse agroecosystems exhibit greater resilience to climate change, providing vital ecosystem services such as natural pest control and offering a wide range of nutritious food (Aguilar et al., 2015; Mori et al., 2017). To enhance the resilience of the agriculture ecosystem to climate change and sustain ecosystem services, regions with low crop diversity should consider diversifying their crops. Similarly, regions with high forest and grassland coverage can promote agricultural value and improve farmer welfare by developing organic agriculture, agroforestry systems, and recreational farming based on biological resources and crop diversity (Hu et al., 2022).

4.1. Limitations and future recommendations

This study focuses on horizontal comparative assessments at the county level to help identify each county's comparative advantages and disadvantages. However, it does not include a longitudinal assessment of agricultural sustainable development. Future studies should consider this longitudinal study, as sustainability is a dynamic process. Meanwhile, it's crucial to analyse the interactions among factors influencing agriculture development to have a better grasp of agricultural sustainability (Bastan et al., 2018; Kanter et al., 2018). Future research should conduct qualitative comparative analyses of all agriculture-related factors to determine their interplay. Also, factors such as effective waste management and adaptation to climate change should be applied in future studies as they are crucial for achieving agricultural sustainability.

Notably, this study provides an assessment framework that serves as a road map for assessing and enhancing agricultural sustainability and offers some general suggestions based on the agricultural sustainability performance of the study area. Detailed suggestions for specific issues are beyond the research scope of this study. Future research could compare specific indexes and provide tailored suggestions for local stakeholders.

Future research on agricultural sustainability should consider the unique hydrological geography and socio-economic conditions of the study area, offering insights into promoting agricultural sustainability based on its specific characteristics. For example, the geographical composition and good-quality cropland indexes applied in this study were tailored to Yunnan.

5. Conclusion

This study comprehensively assessed the performance of agricultural sustainability in Southwest China, with a focus on Dali Prefecture, Yunnan Province. Using the DPSIR framework, this study chooses 33 indexes to analyse factors affecting agricultural sectors, offering a roadmap for enhancing agriculture sustainability in Southwest China. Existing research on agricultural sustainability in China primarily concentrated on economically developed areas with relatively flat terrain, overlooking the understanding of agricultural sustainability in Southwest China or Yunnan Province – an area characterized by its less developed status and mountainous terrain. This study aims to fill this research gap.

Based on the assessment system, this study found that agricultural sustainability performance varies across the entire Dali prefecture, ranging from 25.653% to 66.807% at the county level, with a mean value of 40.993%. Regions with higher values were primarily located in the central and northeast, while those with lower values were concentrated in the west and southwest (where the terrain is steepest in Dali Prefecture). Dali City, the capital of Dali Prefecture, had significantly better sustainability performance, being 1.46 times that of second-ranked Xiangyun County and 2.6 times that of last-ranked Yunlong County. High-scored regions, for instance, Dali City and Xiangyun County received the highest scores on the Response criterion, while other regions were found to score low in the response criterion.

Based on both subjective (expert judgment) and objective (data statistics) methods, this study analysed the composite weights for DPSIR's five factors, identifying the importance and contribution order as follows: Response > State > Pressure > Impact > Driver. The Response criterion holds the highest position and has a score ratio 2.62 times greater than the second-ranking criterion. This novel finding holds significance for future studies on agricultural sustainability, both within and beyond China. In terms of importance, Responses taken by stakeholders to address unsustainable development challenges are crucial. In contrast, Drivers such as land urbanization and population urbanization, which lead to unsustainable change in agriculture in China, are less significant compared to other indicators. Governments should put more emphasis on Response-related factors when advancing the sustainability of agriculture. For example, effective extension activities and training programmes for farmers should be designed to improve their understanding of organic agriculture, and irrigation infrastructure should be improved to increase rural households' access and use efficiency of water (especially in drought-affected areas like study area), agricultural machinery should be adapted to meet the specific requirements of small-scale terraced farming and mountainous farming, and projects and initiatives aimed at improving farmers' financial stability and living standards should be customized to suit local circumstances, among other measures. Furthermore, the results of index weights derived from subjective and objective methods indicate that experts consider the index associated with land resources and farming activities unimportant despite the data suggesting otherwise. Conversely, indexes related to social welfare, public infrastructure, and economic development are considered more important by experts but not by the data.

The longitudinal assessment of sustainable development of agriculture and the analysis of the interactions among agricultural-related factors are not within the scope of this study, but they could be explored in future studies. This study provides general suggestions based on the agricultural sustainability performance of the study area, while detailed suggestions for specific issues are outside the scope of this study. Future research could compare specific indexes and offer tailored suggestions for local stakeholders. Additionally, factors such as effective waste management and adaptation to climate change were not included in this study due to data availability limitations, but they could be considered in future studies.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability

Data will be provided upon a reasonable request by the first author.

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